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Shower reconstruction in the ATLAS ZDC

1 Introduction

A Zero Degree Calorimeters (ZDCs) for ATLAS experiment at LHC is employed to detect forward going neutral particles (mainly photons and neutrons) with energies above 100 GeV. Due to the high radiation environmental conditions, a detection agent of the Calorimeter was chosen to be Cerenkov light produced in the quartz rods penetrating the calorimeter. Each ZDC is assembled of 4 tungsten modules ($29X_0$ or $1.14\lambda_{\mathrm{int}}$) aligned along the beam. The first module, which capture all photons, is called electromagnetic module (EM) while the rest three are called hadronic modules (HM). All modules are readout (see Fig. 1) by "strips" which are "made of" vertically arranged 1.5 mm diameter rods. In addition, for coordinate measurements the EM and first HM contain 96 rods of 1 mm diameter, arranged in 8×12 matrix with 1 cm spacing. While there is only one rod per readout channel in the EM, every four rods (2×2 matrix) are viewed by one PMT channel in the HM.

ZDC is designed to provide energy resolution of 4% for 1 TeV photons and 17% for 1 TeV neutrons. A spatial resolution is expected to be less than 0.5 mm for 1 TeV photon and less than 1 mm for 1 TeV neutrons.

To achieve such performance an adequate methods of shower reconstructions have to be developed. As well, proper calibration and monitoring during the LHC run has to be provided.

2 Strip readout for energy and time measurements

The strip readout is designed for time and energy measurements. There are only a few readout channels to be calibrated, 4 PMTs in the EM, and one PMT per each HM. One can isolate two main stages of the strip readout calibration,

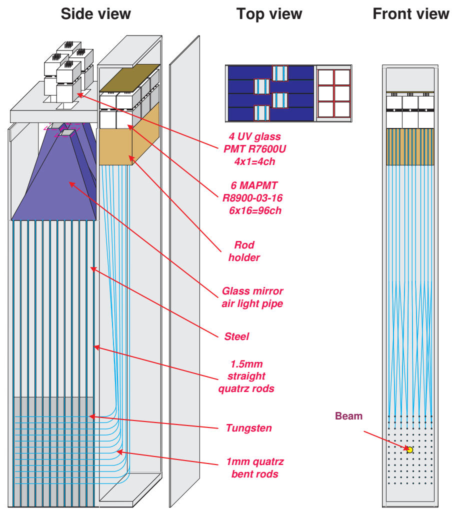

Figure 1: Electromagnetic ZDC module. Beam impinges on tungsten plates at bottom of module, and showers. Quartz rods pick up Cerenkov light from shower and pipe it to multi-anode phototube at top of module. Phototubes measure light from strips through four air light pipe funnels.

(i) relative adjustment of all channels to each other and *(ii)*common scaling of all calibration coefficients. A "perfect" source for such calibration ,neutrons with known energy in a TeV range are not expected to be available. Test beam protons with energies of about 200 GeV are not good enough for this purpose, at least, because extrapolation of result of calibration to the TeV region may be not reliable.

According to Pythia simulation, the energy spectra of an isolated hadron (mainly neutron) observed by ZDC has maximum at about 3 TeV, as shown in Fig. 2. Since, the width of this distribution ($\sim 50\%$) is comparable with the hadron energy resolution ($\sim 15\%$), one can relatively adjust all gains even if the exact position of the energy distribution maximum is not known. For this purpose, a regular calibration procedure may be applied assuming that all hadrons has the same energy of, *for example*, 3 TeV. For the second stage of the calibration, determining a common scale of the calibration coefficients, we consider $\Lambda \to n\pi^0$ decays as a source of tagged neutrons with known (reconstructed) energies. In such process we can tag neutron energies above 2 TeV.

I the Heavy Ion run, a detection of the isolated neutrons carrying the nominal beam energy of 2.75 TeV is possible. We can use such neutrons for the ZDC calibration.

An important constituent of the calibration is the study of the signal dependence on the x-coordinate of the particle. This dependence is caused by the gaps between strips. Such calibration (or precalibration) may be done prior the

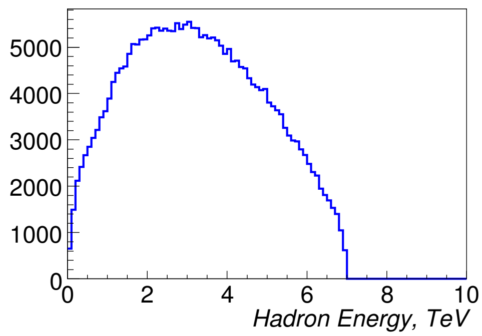

Figure 2: Isolated hadron energy in the ZDC as simulated by Pythia.

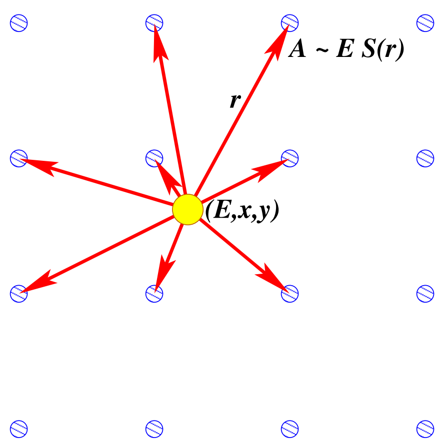

Figure 3: A schematic picture of the shower detection in horizontal rods (pixel readout).

LHC run, for example, in stand alone test beam measurements. A pixel readout give us an opportunity to make calibration (or to monitor the pre-calibration) during the LHC run.

A strip readout calibration of the EM for electromagnetic processes (photon detection) may be done in parallel with the calibration of pixel readout as it is described below.

3 Pixel readout for coordinate measurements

The main purpose of pixel readout is measurement of the coordinates of photons and neutrons, however it also allows us to measure energy (with accuracy about twice worse compared to the strip readout). This energy measurement is essential in the reconstruction of the multihit events such as decays $\pi^0 \to \gamma\gamma$, $K_S \to \pi^0\pi^0 \to 4\gamma$, $\lambda \to n\pi^0 \to n\gamma\gamma$, e.t.c..

Pixel readout is schematically illustrated in Fig. 3. Since horizontal rods which are sensitive elements of the pixel readout have a small transverse size and occupy only about 1% of the ZDC volume, a signal amplitude in a rod may

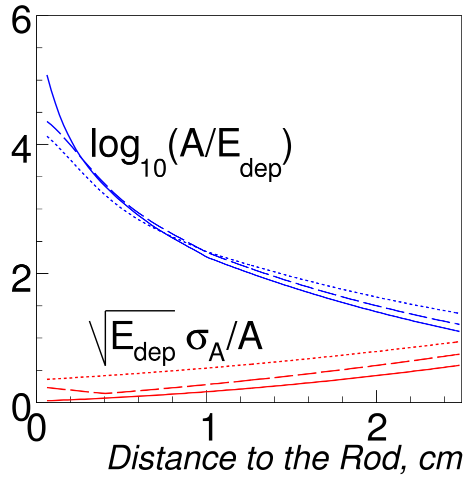

Figure 4: The mean value and variance of the rod amplitude dependence on the distance to the shower center. The rod amplitude A is given in number of photo-electrons and deposited energy E_{dep} is given in TeV units. Solid line stands for electromagnetic shower, dashed and dotted lines are for the hadronic shower in electromagnetic and hadronic ZDC modules, respectively.

be approximated by a dependence

$$A = cES(r) \tag{1}$$

where E is energy deposited in ZDC module (photon energy for electromagnetic module), $S(r)$ is shower shape function which depends only on the distance between shower center and a rod, and c is normalization factor which is proportional to the photodetector gain. If function $S(r)$ is known, amplitude measurement in at least 3 rods allows us to unambiguously determine the energy and coordinates of the shower. If more amplitudes are measured, shower parameters may be improved in the fit by minimizing the 3-dimensional function

$$\Phi(E, x, y) = \sum_i \left(\frac{A_i - c_i E S(r_i)}{c_i \sigma_S(r_i, E)} \right)^2 \tag{2}$$

Here, index i numerates rods and $\sigma_S(r, E)$ is RMS of the amplitude fluctuations depending on the distance to the shower center and shower energy.

In fact, both functions $S(r)$ and $\sigma_S(r, E)$ depends on the particle energy and, in case of hadronic shower, on the z-coordinate of the shower starting point. However, we have found in our Monte-Carlo simulation that a naive approach that the following modified functions

$$\tilde{S}_r(r) = S(r) \sim \frac{A}{E} \quad \text{and} \quad \tilde{\sigma}_r(r) = \sqrt{E}\,\frac{\sigma_S(r, E)}{S(r)} = \sqrt{E}\,\frac{\sigma_A}{A} \tag{3}$$

depend only on the distance to the shower is sufficient for ATLAS ZDC data analysis.

Geant based calculations of the rod mean amplitude and its variance as a function of the distance to the center of the shower are shown in Fig. 4. These

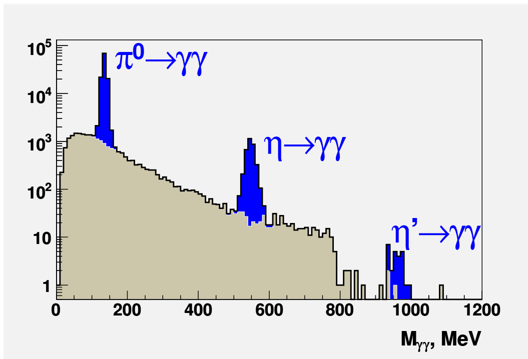

Figure 5: Simulated $\gamma\gamma$ mass spectrum for two-photon events in ZDC

calculations were done with 1 TeV photons and 2.75 TeV neutrons, however, it was found that shown distributions are almost insensitive to the actual energy of the particle. We note that shower shape functions are different for electromagnetic and hadronic showers. Also hadronic shape functions are different for the first (electromagnetic) and second (hadronic) ZDC modules.

It was found that rod amplitudes fluctuations may be considered as uncorrelated in the electromagnetic shower fit. This is not quite true for the hadronic shower. Since ZDC module is only 1.2 interaction lengths, the deposited energy and effective width of the shower significantly depends on z-coordinate of the beginning of hadronic shower. For this reason, a modified rod amplitude

$$A = cES(kr)/k^2 \tag{4}$$

with a scaling factor k being a free parameter in the fit (but being the same for all rods in a shower), allows one to improve the results of the fit.

Obviously, the shape function $S(r)$ is defined in Eq. (1) up to an arbitrary factor (c). To resolve the ambiguity we can assume $S(1\text{ cm}) = 1$. The full calibration of the ZDC electromagnetic module pixel readout includes the determination of the shape function $S(r)$ and normalization (calibration) coefficients c for each of 96 rods. A straight way to do such calibration is to expose ZDC module by photons (electrons) with known energy and coordinates. Since we do not expect such possibility in the LHC run, we are developing an alternative method of calibration using isolated photons in a TeV range. Definitely, the very strong dependence of $S(r)$ on r limits the capability of pixel readout for energy measurements. On the other hand, as it directly follows from Fig. 3, such strong dependence provides good coordinate resolution even if $S(x)$ is poorly known In other words, if more than 3 rods are hit, we can imply constraints on the calibration coefficients and/or shape function even if the energy and coordinates of the photons are unknown. If energy of photons is unknown, we can determine calibration coefficients c only up to a common factor. In turn, this factor may be found by detecting $\pi^0 \to \gamma\gamma$ decays (see Fig 5).

This method was proven for electromagnetic module in a Monte-Carlo simulation. For hadronic module in which one readout channel includes four rods and there are significantly larger fluctuations of each rod amplitude, the method is more problematic. We continue to work on these problems.

The shower analysis based on Eq. (2) is very natural for the separation of the overlapping showers. For n partially overlapped showers we should minimize the $3n$-dimensional function

$$\Phi(E_\mu, x_\mu, y_\mu) = \sum_i \frac{\left(A_i - c_i \sum_\mu E_\mu \tilde{S}_r(r_{i\mu})\right)^2}{c_i^2 \sum_\mu E_\mu \tilde{\sigma}_r^2(r_{i\mu}) \tilde{S}_r^2(r_{i\mu})}, \tag{5}$$

where symbol μ specifies the shower number, $r_{i\mu}$ is the distance from i-th rod to the center of μ-th shower, and functions $\tilde{S}_r(r)$ and $\tilde{\sigma}_r(r)$ are defined in Eqs. (1,3).

We applied this method to reconstruct Monte-Carlo $K_S \to \pi^0\pi^0$ decays for which ZDC module is heavily populated with 4 electromagnetic showers. It was found that electromagnetic showers with energies above 100 GeV may be separated effectively if the distance between shower centers is more than 1.2 cm.